UNITED STATES PATENT APPLICATION

FOR

EXTRACTING FINE-TUNED ESTIMATES FROM CORRELATION FUNCTIONS EVALUATED AT A LIMITED NUMBER OF VALUES

INVENTORS:

ANANT SAHAI
JOHN TSITSIKLIS
STEFANO CASADEI
ANDREW CHOU
BENJAMIN VAN ROY
JESSE ROBERT STONE

PREPARED BY:

HICKMAN PALERMO TRUONG & BECKER LLP
1600 WILLOW STREET
SAN JOSE, CALIFORNIA 95125
(408) 414-1080

EXPRESS MAIL CERTIFICATE OF MAILING

"Express Mail" mailing label number EL734779448US

Date of Deposit JUNE 22, 2001

I hereby certify that this paper or fee is being deposited with the United States Postal Service "Express Mail Post Office to Addressee" service under 37 CFR 1.10 on the date indicated above and is addressed to the Assistant Commissioner for Patents, Washington, D.C. 20231.

Carina M. Tai
(Typed or printed name of person mailing paper or fee)

Carina M. Tai
(Signature of person mailing paper or fee)

EXTRACTING FINE-TUNED ESTIMATES FROM CORRELATION FUNCTIONS EVALUATED AT A LIMITED NUMBER OF VALUES

FIELD OF THE INVENTION

The present invention relates to signal processing and, more particularly, to techniques for extracting fine-tuned estimates from correlation functions evaluated at a limited number of values.

BACKGROUND OF THE INVENTION

In the context of signal processing, when a signal is transmitted to a receiving device, there is a certain amount of unknown delay associated with the propagation of the signal. The original signal is not received instantaneously at the receiving device. A calculated estimate of the delay associated with the received signal is generally limited to the resolution of the sampling rate of the received signal. For example, if the received signal can be represented as a continuous integrable function, $x(t)$, then the received signal, which typically contains noise, may be converted to a discrete sequence of values in time through sampling. The discrete sequence of values is herein referred to as sampled data. As the sampling rate increases, the sampled data becomes a more accurate representation of $x(t)$. Due to the finite sampling rate, the delay value that is calculated from the sampled data is not as precise as the delay value calculated from a continuous function.

In one approach, a more accurate delay value estimate may be obtained by adjusting the sampling times. For example, correlation calculations can be performed for a pair of delay values that produce equal values in the magnitude calculations of

the correlation integrals. If the magnitude values corresponding to the pair of delay values are high enough, then it may be assumed that the peak magnitude, and hence the true time delay, lies halfway between the pair of delay values (used in the delay lock loop). However, a significant drawback with this approach is that it assumes that the sampling times can be adjusted, and that it is already known where to look approximately. If the sampling times cannot be adjusted, (i.e., the set of sampled data with which to work is fixed), then in general a different reference signal needs to be used in computing the correlation integrals at the different delay. It may not be enough to just time shift the reference by an integer number of samples.

Another approach for estimating a delay value at a level of precision that is higher than the precision corresponding to the sampling rate, is to adopt a fine-grid for a hypothesized range of delay values. In such an approach, the sampled data is correlated against the reference signal by shifting the reference signal according to the fine gridding of delay values. The correlation between the received signal and the reference signal is performed by calculating the In Phase ("I") and Quadrature ("Q") correlation integrals for the range of hypothesized delay values, which is finely gridded, at the specified modulation frequency. But the finer the gridding of the search region gets, the more correlations must be computed. Thus, a disadvantage with using a fine grid for searching over the hypothesized range of delay values is that the high cost of computing the correlations, especially when there is a considerable amount of sampled data, (i.e., the sampling duration is long) can be computationally prohibitive. Based on the foregoing, there is a clear need for a technique for estimating

the delay associated with a received signal in a cost effective fashion during signal processing.

A very similar problem arises when the received signal is modulated by an unknown frequency and one needs to derive a fine-tuned estimate of this frequency from a set of IQ correlations obtained by searching over a coarse-grained set of frequencies representing the uncertain region.

SUMMARY OF THE INVENTION

Techniques are provided for fine-tuning estimates of a delay value and other parameters of interest associated with a sampled signal. One aspect of the invention is to use, for the sampled signal, calculations of the In Phase and Quadrature (I and Q) correlation integrals at a limited number of coarsely spaced points, wherein the calculations are performed for a set Σ_1 of hypothesized delay values. These coarse-grained IQ correlations can be carried out by means of dedicated hardware, or the method described in U.S. Patent Application No. / , , filed on the same day herewith, entitled "Synthesizing Coherent Correlation Sums at One or Multiple Carrier Frequencies Using Correlation Sums Calculated at a Coarse Set of Frequencies", by inventors Anant Sahai and John Tsitsiklis, (Attorney Docket No. 60021-0012), or any other possible way. A subset of I and Q correlation values based on the coarse granularity calculations of the I and Q correlation functions is used to perform an interpolation to obtain fine-grained values of the I and Q integrals in the range of the delay, or other parameter, values of interest. Searching over such interpolated values effectively produces correspondingly fine precision estimates of the delay, or other parameter, values in the range of interest.

Another approach used in this invention to calculate fine precision estimates is based on a template-matching approach whereby the received signal is compared with a parametric template.

This invention can also be used to estimate parameters other than the delay, such as the modulation frequency or other characteristics of the received signal.

In general, these estimates can be given in the form of a single optimal value, an interval, a collection of intervals or a set of values.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings and in which like reference numerals refer to similar elements and in which:

FIG. 1 is a block diagram that illustrates a system overview for processing a signal;

FIG. 2 is a flowchart that illustrates a technique for fine-tuning estimates of delay in time associated with a received signal;

FIG. 3 is a flowchart that illustrates a template-based approach to calculate fine-tuned estimates of the delay and other parameters;

FIG. 4 is a block diagram illustrating a computer system on which embodiments of the invention may be implemented.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Techniques are provided for fine-tuning estimates of a delay and other parameter values associated with a sampled signal. In the following description, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, to one skilled in the art that the present invention may be practiced without these specific details. In other instances, well-known structures and devices are shown in block diagram form in order to avoid unnecessarily obscuring the present invention.

SYSTEM OVERVIEW

FIG. 1 is a block diagram that illustrates a system overview for processing a signal. System 100 comprises a signal source S, a receiver H, and a server D. In this example, the analog signal is transmitted to receiver H. The signal that is received at H is herein referred to as a "received signal". It is assumed that there is an unknown delay from the time the analog signal leaves signal source S and when it is received at receiver H. Such a delay is herein referred to as a "delay value". In one embodiment of the invention, receiver H converts the analog signal into discrete sequence of values as a function of time by digitizing the received signal. The digitized received signal is herein referred to as a "sampled signal" or "sampled data". In one embodiment, receiver H transmits the sampled data to server D for processing. For the purpose of explanation, signal source S may be a transmitter or beacon like a Global Positioning System (GPS) satellite vehicle from a set of GPS satellite vehicles that is overhead the location of receiver H. Examples of receivers are Global

Positioning System receivers, cell phones with embedded signal receivers, Personal Digital Assistants (PDAs) with embedded signal receivers, etc. Further, in certain embodiments, receiver H may transmit the sampled data to a base station (not shown in FIG. 1), which in turn transmits the sampled data to server D for processing, as further described in U.S. Patent Application Serial No. 09/730,324, filed December 4, 2000, entitled "Methods and Apparatus for Determining Location Using a Thin-Client", by inventors Benjamin Van Roy, Andrew Chou and Sherk Chung

FUNCTIONAL AND OPERATIONAL OVERVIEW

This invention reduces the amount of computation needed to calculate fine precision estimates of the delay (or other parameters such as the exact Doppler shift) of the signal by means of a two-stage approach. Although the description here focuses on estimating delay, one of ordinary skill in the art should see how to use this invention to estimate other parameters of interest. The first stage considers only a coarse set of possible delay values and produces one or more approximate delay estimates. The strength or likelihood of candidate delay values is evaluated either directly by the square-magnitude of the IQ correlations, I^2+Q^2, or by comparing the IQ correlations with a template (*template-matching* method). The IQ correlations are standard In-phase and Quadrature correlations of the sampled signal with a suitably modulated reference signal representing the known signal being searched for.

The second stage refines these approximate delay estimates by performing either an interpolation or finer template-matching operation in a neighborhood of these coarse estimates. It avoids the expense of recalculating the IQ correlations at the

finer resolution.

DETERMINING FINE-TUNED ESTIMATES OF DELAY VALUES

FIG. 2 is a flowchart that illustrates the simplest embodiment of a technique for fine-tuning estimates of delay values associated with a received signal. FIG. 3 illustrates the technique based on template-matching. In certain embodiments of the invention, server D performs the steps as described herein with reference to FIG. 2 and FIG. 3.

Coarse IQ Correlation: At block 220, coarse-grained calculations of IQ correlation integrals are performed for the sampled data at a set Σ_1 of hypothesized delay values. The determination of a range of hypothesized delay values can be based on the uncertainty in certain basic variables like space and time, or might be known from other sources depending on the application at hand. Determining this range is further described in U.S. Patent Application Serial No. / , , filed on the same day herewith, entitled "Determining the Spatio-Temporal and Kinematic Parameters of a Signal Receiver and Its Clock by Information Fusion", by inventors Anant Sahai, Andrew Chou, Wallace Mann and Stefano Casadei, (Attorney Docket No. 60021-0014). In one embodiment of the invention, described further in U.S. Patent Application No. / , , filed on the same day herewith, entitled "Signal Acquisition Using Data Bit Information", by inventors Anant Sahai, Wallace Mann, Andrew Chou and Benjamin Van Roy (Attorney Docket No. 60021-0011), the coarse-grained calculations are carried out together by dividing the sampled signal into a plurality of blocks of data.

Alternatively, the coarse-grained calculations can be carried out individually in the direct manner well known to those skilled in the art.

The coarse-grained IQ correlations can also be carried out by means of dedicated hardware, or the approximate method described in U.S. Patent Application No. / , , filed on the same day herewith, entitled "Synthesizing Coherent Correlation Sums at One or Multiple Carrier Frequencies Using Correlation Sums Calculated at a Coarse Set of Frequencies", by inventors Anant Sahai and John Tsitsiklis, (Attorney Docket No. 60021-0012), or by any other known technique.

The underlying IQ correlations at hypothesized delay τ are denoted by the complex signal $z(\tau) = I(\tau) + jQ(\tau)$. The coarse-grained IQ correlations can be represented by a discrete sequence $z[k]$ of complex numbers where the k-th point in the sequence is $z(\tau)$ evaluated at $\tau = k\Delta$ where Δ denotes the inter-sample time.

Magnitudes: At block 230, the magnitudes $|z[k]| = \sqrt{I^2[k] + Q^2[k]}$ of the coarse-grained IQ correlation integrals are calculated. The magnitude of the continuous-time correlation function $|z(\tau)|$ is assumed to be large (e.g. above a threshold) or maximum when τ is at or near the true delay.

Computation of coarse delay estimate(s) (or "initial estimate of delay values"): At block 240, one or more coarse values of the delay, herein referred to as "initial estimates of delay values," are selected by using one of the following methods. The set of selected values is denoted by Σ'_1. One method is to choose the single value

of $k\Delta$ that maximizes $|z(k\Delta)|$:

$$\Sigma_1' = \{\operatorname{argmax}_{k\Delta} |z(k\Delta)|\}.$$

Another method is to select an interval of values around the maximum. One skilled in the art can see how statistical methods can be used to determine the size of this interval given a specified confidence level and suitable statistical assumptions relevant to the exact situation at hand.

Another method is to choose all the values $k\Delta$ for which $|z(k\Delta)|$ is above a threshold b:

$$\Sigma_1' = \{k\Delta : |z(k\Delta)| > b\}.$$

One skilled in the art can see how statistical methods can be used to determine this threshold given a specified confidence level and suitable statistical assumptions relevant to the exact situation at hand.

Fine-grained values of interest (or "range of delay values of interest"): At block 250, a set $\Sigma_2 =$ of delay values in the neighborhood of the initial estimate of delay value is selected to represent the new range of delay values of interest. For instance, these values of interest can be chosen to be:

$$\Sigma_2 = \left\{ iP + j\Delta, \qquad i = 0, \pm 1, \pm\frac{\Delta}{P}, \quad j\Delta \in \Sigma_1' \right\} \tag{1}$$

where $j\Delta$ is one of the selected coarse values of the delay, (also referred to as "selected initial estimate of delay value") and P is the desired precision.

Fine-grained interpolation At block 260, fine-grained values for the I and Q correlation integrals are interpolated by using a subset of the coarse-grained calculations of the I and Q correlation integrals. The fine-grained values for the I and Q correlation integrals can then be searched to give rise to fine-tuned estimated delay values. Various interpolation techniques may be used for interpolating the fine-grained and Q correlation integrals. As one skilled in the art knows, there are a variety of well known interpolation techniques and which one is suitable may vary from implementation to implementation. One such technique is bandlimited interpolation.

If the IQ correlation integral $z(\tau)$ is presumed to have bandwidth $1/2\Delta$ or less viewing delay τ as the virtual time variable, then the fine-tuned value of the IQ correlation $z(\sigma_2)$, $\sigma_2 \in \Sigma_2$ is computed by interpolating the Δ-spaced samples $z(k\Delta)$ by means of a sinc weighting function:

$$z(\sigma_2) = \sum_{k:|\sigma_2 - k\Delta| < R_1} z(k\Delta) \frac{\sin[\pi(\sigma_2 - k\Delta)/\Delta]}{\pi(\sigma_2 - k\Delta)/\Delta}, \quad \sigma_2 \in \Sigma_2$$

The cutoff value R_1 at which the sum is truncated can be determined according to the accuracy desired, as one skilled in the art can readily see. The larger the desired accuracy, the large R_1 should be made.

Finally, block 270 selects a set Σ_2' of fine-tuned estimates of delay values by using one of the same set of possible methods that could be used in block 240.

Alternatively, the interpolation above could be carried out using the real valued $|z(\tau)|$ rather than the complex $z(\tau)$ if the approximation loss is acceptable.

TEMPLATE-BASED APPROACH

FIG. 3 is a flowchart that illustrates another technique for fine-tuning estimates of delay values and other parameters associated with a received signal. For this technique, it is assumed that the ideal shape of the IQ correlation integral $z(t)$ is known and is represented by a *parametric template* $S_\mu(t)$ parametrized by μ. When the hypothesized source produces and transmits a signal, the IQ correlation $z[k]$ is assumed to contain an *image* of the template S_μ given by $S_\mu(t-\sigma)$, where σ is the delay. The observed IQ correlation integral $z(t)$ is modeled to be

$$z(t) = S_\mu(t-\sigma) + \text{noise}.$$

The parameters of the template (other than the delay), denoted collectively by the symbol μ, account for the variability in the received signal due to a variety of modeled phenomena, which may include signal attenuation, frequency shifts, and multipath propagation. For example, the IQ correlation integral for GPS signals in the presence of multipath contains the interaction of two or more low-passed triangular waveforms that are scaled and shifted with respect to each other by amounts that vary in a continuum of possible values. Other variability is due to some signal processing parameters (such as the bandwdith of certain filters) that are known for the particular signal being processed but can vary between signals.

One form for the template that is considered:

$$S_\mu(t-\sigma) = A_1 S_\theta^{(1)}(t-\sigma) + \ldots + A_N S_\theta^{(N)}(t-\sigma),$$

where the parameter μ comprises both the linear parameters $A_1, \ldots, A_N$ and the remaining nonlinear parameters (other than the delay σ) θ.

The template-matching approach consists in finding estimates of the parameters for which the total weighted square error

$$\lambda_\mu(\sigma) = \sum_k w_\mu(k\Delta - \sigma) \left| z(k\Delta) - S_\mu(k\Delta - \sigma) \right|^2$$

is small or minimal. The weights w_μ, which are optional and could just be set to 1, can be used to emphasize certain portions of the template which are known to be more reliable or important for the specific situation at hand.

The description of the template-matching approach is as follows.

At block 310 of FIG. 3, a parametric family of templates $S_\mu(t)$, $\mu \in \mathcal{M}$ is chosen. If weights are used, a weighting function w_μ for each parameter $\mu \in \mathcal{M}$ is constructed. Block 310 can be executed off-line. More details about this block are in the section entitled "Template construction".

Block 320 determines a coarse set of delay values (also referred to as "initial estimates of delay values"), Σ_1, and non-linear parameters, Θ_1, which presumably contain a good approximation to the unknown value of the parameter θ and delay σ. A loop is initiated that hypothesizes each of these values and control is passed to Block 330.

Block 330 performs a linear regression to estimate the linear parameters $\underline{A} = (A_1, \ldots, A_N)$ that minimize the weighted square error for each of the hypothesized non-linear parameter θ_1 and delay values $k\Delta$. For instance, if there is only one linear parameter,

$$A(k\Delta, \theta_1) = \frac{\sum_{k'} w_\mu(k'\Delta - j\Delta) S_{\theta_1}{}^*(k'\Delta - j\Delta) z[k']}{\sum_{k'} w_\mu(k'\Delta) \left| S_{\theta_1}(k'\Delta) \right|^2}, \qquad k\Delta \in \Sigma_1, \theta_1 \in \Theta_1.$$

Block 340 selects a subset of the hypothesized coarse values of the delay (also referred to as "selected initial estimates of delay values") and other nonlinear parameters according to the value of the minimum total weighted square error $\lambda(k\Delta, \theta_1)$, equal to the total weighed square error $\lambda_\mu(k\Delta)$ minimized over all linear parameters $\underline{A}$.

One method is to choose the value of these parameters that minimizes $\lambda(k\Delta, \theta_1)$.

Another method is to select a range of values around the minimim and represent them by an uncertainty interval. One skilled in the art can see how a statistical method can be used to determine the size of this interval given a specified confidence level and suitable statistical assumptions relevant to the exact situation at hand.

Another method is to choose all the values for which $\lambda(k\Delta, \theta_1)$ is below a threshold. One skilled in the art can see how a statistical method can be used to determine the threshold given a specified confidence level and suitable statistical assumptions relevant to the exact situation at hand.

The selected subsets of coarse delays (also referred to as "selected initial estimates of delay values") and nonlinear parameters is denoted Σ_1' and Θ_1'.

Block 350 selects a fine-tuned range of delay values that are also referred to as a "range of delay values of interest", and nonlinear parameters in the neighborhood of each selected coarse value (i.e., of each "selected initial estimate of delay values"). For example, the following fine-grained values of the delay (i.e., "range of delay values

of interest") can be considered:

$$\Sigma_2 = \left\{ iP + k\Delta, \quad i = 0, \pm 1, \pm\frac{\Delta}{P}, \quad k\Delta \in \Sigma_1' \right\}.$$

Block 360 is analogous to block 330, but is performed on the fine-grained set of delay values (range of delay values of interest)and nonlinear parameters. However, since the hypothesized values are much closer to each other, one can obtain significant computational savings by using an interpolation technique whenever the underlying functions are sufficiently smooth.

For example, in the case when there is only one linear parameter A, and a bandlimited assumption is valid, then an interpolation method similar to the one used in block 260 can be used:

$$A(\theta, \sigma_2) = \sum_k A(\theta, k\Delta) \frac{\sin[\pi(\sigma_2 - k\Delta)/\Delta]}{\pi(\sigma_2 - k\Delta)/\Delta}, \qquad \sigma_2 \in \Sigma_2$$

If the bandlimited assumption is not valid, then one needs to solve the linear regression problem for each of the hypothesized fine-grained values and search over the results. For example,

$$A(\theta, \sigma_2) = \frac{\sum_k w_\mu(k\Delta - \sigma_2) S_\theta^*(k\Delta - \sigma_2) z[k]}{\sum_k w_\mu(k\Delta - \sigma_2) \left| S_\theta(k\Delta - \sigma_2) \right|^2}, \qquad \sigma_2 \in \Sigma_2 \qquad (2)$$

This computation is done in slightly different ways depending on whether the template μ and the weights w_μ are encoded by an analytical expression or by a table. One skilled in the art can implement a system to evaluate the expression (2) and search for an estimate in a satisfactory way according to the relevant constraints and requirements by means of exhaustive search, divide-and-conquer, gradient descent, Newton's method, and a host of other optimization techniques.

One skilled in the art will also see that in a small neighborhood of a nominal value for a nonlinear parameter, the effect of that parameter on the template can be well approximated by a linear term using a Taylor expansion. Such a method can be used to help aid the search over some of the otherwise nonlinear parameters in small local neighborhoods. One skilled in the art can use this to speed up the search even further by linearizing nonlinear parameters based on the neighborhoods in question.

For certain types of templates, it is possible to estimate the delay and amplitude of the template by means of an exact N-point fitting of the function $S_\mu(t-\sigma)$ to the observed IQ correlation integral. This is accomplished by solving the system of N nonlinear equations

$$S_\mu(k\Delta - \sigma) = z(k\Delta), \qquad k = j_1, j_1 + N,$$

whose unknowns are the delay σ, and the $N-1$ unknown parameters in μ of the template. One skilled in the art will notice that the although the above equations are written for a sequential set of correlation integrals, the N equations can also be made from any set of N observed correlation integrals.

An important application of this method is to searching for an estimate for the exact modulation frequency parameter $\overline{f}$. The analogous calculations are performed, but with the search over the delay parameter σ replaced with a search over the modulation frequency f. The equations are

$$S_\mu(k\Delta - \overline{f}) = z(k\Delta), \qquad k = j', j' + 1,$$

where Δ is now a frequency interval and the template $S_\mu(f)$ can be taken equal to

the expression

$$S_\mu(f) = A\frac{\sin^2[\pi f/\Delta]}{\pi^2 f^2/\Delta^2}.$$

In this particular choice of template for estimating the frequency, the unknown parameters are just the amplitude A and the $\bar{f}$ representing the true modulating frequency. This template is an approximation to the case where the underlying correlation sums are taken over a large number of data points. Other templates might be suitable if the underlying correlation sums are computed differently.

Block 370 is exactly analogous to block 340.

TEMPLATE CONSTRUCTION

In one embodiment of this invention, which calculates delay estimates of a GPS signal, the basic template is obtained by convolving the appropriately lowpass filtered PRN code (i.e. the appropriate PRN code filtered by the lowpass filter $H_{W,\alpha}$) with itself. This basic template will be denoted $g_{W,\alpha}$

$$S_\mu(t-\sigma) = Ag_{W,\alpha}(t-\sigma).$$

The parameter W denotes the bandwidth of the filter and α denotes other parameters that describe the shape of the filter. The template has roughly the shape of a rounded triangular peak with a few smaller peaks on the sides.

Among the causes that affect the shape and bandwidth of the filter $H_{W,\alpha}$ are the duration of the correlation integrals, the properties of the A/D converter (and filters therein), and the nature of the approximations during the calculations of the correlation integrals (As those in U.S. Patent Application No. / , , filed on

the same day herewith, entitled "Signal Acquisition Using Data Bit Information", by inventors Anant Sahai, Wallace Mann, Andrew Chou and Benjamin Van Roy, (Attorney Docket No. 60021-0011) and U.S. Patent Application No. / , , filed on the same day herewith, entitled "Synthesizing Coherent Correlation Sums at One or Multiple Carrier Frequencies Using Correlation Sums Calculated at a Coarse Set of Frequencies", by inventors Anant Sahai and John Tsitsiklis, (Attorney Docket No. 60021-0012)).

In more sophisticated embodiments designed to achieve robustness to multipath phenomena, a composite template is constructed out of two or more basic templates. For example, a template with two components is obtained by summing one basic template corresponding to the direct path of propagation and one associated with a reflected path:

$$S_\mu(t-\sigma) = A_1 g_{W,\alpha}(t-\sigma) + A_2 g_{W,\alpha}(t-\sigma-\sigma').$$

Here, σ' is the delay of the reflected waveform relative to the direct waveform and A_1, A_2 represent the complex amplitudes of the two components of the signal.

In general, the parameters that characterize the templates are of two different types: *specified* parameters and *searched parameters.* For the two-composite templates just described, W, α are specified parameters and $A_1, A_2, \sigma, \sigma'$ are searched parameters. The specified parameters are known or selected in advance of the application of this invention, whereas the searched parameters and the image parameters are estimated by means of the processing described by the system in FIG. 3.

Whereas the delay is often the main parameter of interest, many embodiments of the invention can utilize also one of more of the other estimated parameters. The exact Doppler shift of the signal is one other such parameter. One skilled in the art will see that with estimating Doppler, an added consideration is the duration of the received signal that is being correlated. The longer the duration, the more finely spaced in Doppler one needs to have even the coarse-grained points for the estimates to be reliable. One skilled in the art will see that the application of the template fitting approach is not limited to extracting parameters of interest. The goodness of the fit or likelihood can also be used to determine whether the modeled phenomena accurately explain the observed data. For example, even with no explicit modeling of multipath phenomena, the presence of multipath can sometimes be detected by noticing that the goodness of the fit is poor. In such cases, the overal system can take advantage of this information by discounting estimates that come from data which is known to be poorly modeled.

In some embodiments of the invention, the weights w_μ are not used (or equivalently set equal to one). In others, the weights are chosen so as to emphasize the more reliable or significant portions of the template. One skilled in the art will notice that the early portion of a basic template is more reliable because it is less affected by reflected paths. In some embodiments, the weighting function $w_\mu(t)$ is set equal to 1 for $t < t_0$, and equal to 0 for $t \geq t_0$. The details of how $w_\mu(t)$ is chosen can be determined according to the particular situation, as one skilled in the art can see.

In some embodiments of the invention, an analytical expression of the signature

template and/or the weighting function is used. In certain cases, these analytical expressions can be used to fit directly the template to the received signal. Alternatively, one skilled in the art can use these analytical expressions to implement an input/output algorithm that returns the value of the template and/or the weighting function at particular values. In other embodiments, the template and weighting functions are pre-computed and stored in a tabular database that can significantly reduce the amount of time required to carry out the calculations. One skilled in the art can easily determine whether an analytical or a tabular approach is more appropriate to the situation at hand, and such decision can even be made at run-time automatically by suitable automated logic.

HARDWARE OVERVIEW

An embodiment of the invention may be implemented using a computer system that includes a processor for processing information. The Computer system also includes a main memory, such as a random access memory (RAM) or other dynamic storage device, coupled to a bus for storing information and instructions to be executed by the processor. The main memory also may be used for storing temporary variables or other intermediate information during execution of instructions to be executed by the processor. The computer system further includes a read only memory (ROM) or other static storage device coupled to the bus for storing static information and instructions for the processor. A storage device, such as a magnetic disk or optical disk, is provided and coupled to the bus for storing information and instructions.

The invention is related to the use of the computer system for implementing the

techniques described herein. According to one embodiment of the invention, those techniques are implemented by the computer system in response to the processor executing one or more sequences of one or more instructions contained in main memory. Such instructions may be read into the main memory from another computer-readable medium, such as the storage device. Execution of the sequences of instructions contained in the main memory causes the processor to perform the process steps described herein. One or more processors in a multi-processing arrangement may also be employed to execute the sequences of instructions contained in the main memory. In alternative embodiments, hard-wired circuitry may be used in place of or in combination with software instructions to implement the invention. Thus, embodiments of the invention are not limited to any specific combination of hardware circuitry and software.

The term "computer-readable medium" as used herein refers to any medium that participates in providing instructions to the processor for execution. Such a medium may take many forms, including but not limited to, non-volatile media, volatile media, and transmission media. Non-volatile media includes, for example, optical or magnetic disks, such as the storage device. Volatile media includes dynamic memory, such as the main memory. Transmission media includes coaxial cables, copper wire and fiber optics, including the wires that comprise the bus. Transmission media can also take the form of acoustic or light waves, such as those generated during radio wave and infrared data communications.

Common forms of computer-readable media include, for example, a floppy disk,

a flexible disk, hard disk, magnetic tape, or any other magnetic medium, a CD-ROM, any other optical medium, punch cards, paper tape, any other physical medium with patterns of holes, a RAM, a PROM, and EPROM, a FLASH-EPROM, any other memory chip or cartridge, a carrier wave as described hereinafter, or any other medium from which a computer can read.

Various forms of computer readable media may be involved in carrying one or more sequences of one or more instructions to the processor for execution. For example, the instructions may initially be carried on a magnetic disk of a remote computer. The remote computer can load the instructions into its dynamic memory and send the instructions over a telephone line using a modem. A modem local to computer system can receive the data on the telephone line and use an infrared transmitter to convert the data to an infrared signal. An infrared detector coupled to the bus can receive the data carried in the infrared signal and place the data on the bus. The bus carries the data to the main memory, from which the processor retrieves and executes the instructions. The instructions received by the main memory may optionally be stored on the storage device either before or after execution by the processor.

The computer system also includes a communication interface coupled to the bus. The communication interface provides a two-way data communication coupling to a network link that is connected to a local network. For example, the communication interface may be an integrated services digital network (ISDN) card or a modem to provide a data communication connection to a corresponding type of telephone line. As another example, the communication interface may be a local area network (LAN)

card to provide a data communication connection to a compatible LAN. Wireless links may also be implemented. In any such implementation, the communication interface sends and receives electrical, electromagnetic or optical signals that carry digital data streams representing various types of information.

The network link typically provides data communication through one or more networks to other data devices. For example, the network link may provide a connection through the local network to a host computer or to data equipment operated by an Internet Service Provider (ISP). The ISP in turn provides data communication services through the worldwide packet data communication network now commonly referred to as the "Internet". The local network and the Internet both use electrical, electromagnetic or optical signals that carry digital data streams. The signals through the various networks and the signals on the network link and through the communication interface, which carry the digital data to and from the computer system, are exemplary forms of carrier waves transporting the information.

The computer system can send messages and receive data, including program code, through the network(s), the network link and the communication interface. In the Internet example, a server might transmit a requested code for an application program through the Internet, the ISP, the local network and the communication interface. In accordance with the invention, one such downloaded application implements the techniques described herein.

The received code may be executed by the processor as it is received, and/or stored in the storage device, or other non-volatile storage for later execution. In this

manner, the computer system may obtain application code in the form of a carrier wave.

In the foregoing specification, the invention has been described with reference to specific embodiments thereof. It will, however, be evident that various modifications and changes may be made thereto without departing from the broader spirit and scope of the invention. The specification and drawings are, accordingly, to be regarded in an illustrative rather than a restrictive sense.